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(Not to be taken) with a grain of salt: Enhancing perceived saltiness by 3D-printed surface textures

Thomas van Rompay [a,*], Iris van Ooijen [b], Sara Groothedde [a], Daniel Saakes [c]

[a] University of Twente, Enschede, The Netherlands
[b] Behavioral Science Institute, Radboud University, Nijmegen, The Netherlands
[c] KAIST, Republic of Korea

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ABSTRACT

Seeking to promote healthy food options through design, this study investigates whether food saltiness perception can be enhanced through the design of the surface texture of the container from which the product is sampled, using 3D-printing. An experimental study was conducted at a supermarket in which shoppers (N = 270) participated in a taste test. A full-factorial 3 (surface texture: smooth, rough, rough and irregular) × 3 (salt content: low, medium and high salt content) between-subject design was employed. Participants in each condition were asked to try the product and assess saltiness perception, taste intensity, taste liking and willingness to try. Results testify to the feasibility of enhancing saltiness impressions through both rough and irregular 3D-printed surface textures, but only for the medium-salt and high-salt variants. Findings on taste liking and willingness to try likewise testify to the importance of considering the interaction between surface texture and saltiness. These findings qualify previous research on cross-modal correspondences by showing that applications of surface textures may backfire when the gap between expectations triggered by tactile sensations and actual food contents becomes too large. Implications for initiatives aimed at promoting healthy food choices are discussed.

1. Introduction

Although dietary sodium intake (commonly referred to as salt) may vary across populations, nearly all populations around the world consume more than twice the recommended daily amount of sodium (i.e., salt; Kloss, Meyer, Graeve, & Vetter, 2015). Excessive consumption of salt is associated with negative health conditions, including high blood pressure and cardiovascular diseases (Kloss et al., 2015). Additionally, it can adversely affect target organs, including the blood vessels, heart, kidneys, and brain (Farquhar, Edwards, Jurkovitz, & Weintraub, 2015).

Consumer selection and consumption of salty food options is partly motivated by a 'health-pleasure trade off' which reflects the belief that healthy foods and beverages are less tasty than their unhealthy, full-salt, counterparts. Hence, when at the supermarket, consumers feel that they are faced with a choice between *healthy* and *tasty*, and too often (at least from a health promotion perspective) 'tasty' prevails (Raghunathan, Naylor, & Hoyer, 2006; Jo & Jayson, 2018). In addition to such hard-wired heuristics, and of particular relevance to the present undertaking, consumers readily experience reduced-salt foods and beverages as bland or tasteless (Stein, Cowart, & Beauchamp, 2012).

To counteract excessive salt consumption, various initiatives have been developed which either seek to raise consumer awareness of the negative consequences of salt intake (e.g., by means of a traffic light system used in the UK to indicate, amongst others, salt contents), or reduce salt contents in (processed) foods by means of food reformulation. A third (complementary) strategy, which is receiving increasing attention in recent years, seeks to enhance tastiness of healthy food options through design factors of food packaging (e.g., Tijssen, Zandstra, de Graaf, & Jager, 2017; Van Rompay, van Hoof, Rorink, & Folsche, 2019), and tableware (e.g., sample cups and plates; see Van Rompay & Fennis [2019] for a review).

Recent studies underscore the potential of tactile design elements in particular (Barnett-Cowan, 2010; Biggs, Juravle, & Spence, 2016; Carvalho, Moksunova, & Spence, 2020; Krishna & Morrin, 2008; Piqueras-Fiszman & Spence, 2012; Van Rompay & Groothedde, 2019). For instance, in Carvalho et al. (2020), experts and amateurs consumers evaluated specialty coffee served in either a smooth or a rough ceramic cup. Findings showed that experts rated (identical) coffee as more acidic

* Corresponding author at: University of Twente, Department of Communication Science, P.O. Box 217, 7500 AE Enschede, The Netherlands.
E-mail address: t.j.l.vanrompay@utwente.nl (T. van Rompay).

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when sampled from the rough cup, whereas amateurs' sweetness ratings were higher when coffee was tasted from the smooth cup. In line with these findings, and of particular relevance to the current research, Van Rompay and Groothedde (2019) showed that potato chips were evaluated as saltier when sampled from a bowl with a rough (as opposed to a smooth) texture. Importantly however, this effect did not surface for zero-salt chips, suggesting that it is important to consider the gap between expectations triggered by tactile sensations and the nature of the food itself (i.e., actual food contents; Kuenzel et al., 2011).

Extending findings on the impact of design and capitalizing on opportunities provided by 3D-printing (Van Rompay, Finger, Saakes, & Fenko, 2017; Van Rompay, Kramer, & Saakes, 2018), this study seeks to investigate the impact of 3D-printed cups varying in terms of roughness and irregularity on taste evaluation of bouillons with different salt contents. Before elaborating on the details of this study, first we will elaborate on the key constructs involved.

1.1. The influence of tactile design on taste evaluation

When considering the impact of tactile cues on taste evaluation, of key importance are cross-modal correspondences, defined as tendencies for certain sensory features or dimensions from one sensory modality (e.g., touch) to be associated with sensory features or dimensions in another modality (e.g., taste; see Velasco et al., 2016 for a review). In other words, impressions derived from holding a package or cup generate expectations regarding the taste of its contents, which can influence subsequent taste experiences. For instance, in Van Rompay et al. (2018), clientele at an ice cream saloon evaluated lemon ice cream as being sourer when sampled from a sample cup with a sharp (as opposed to a smooth) 3D-printed surface texture. Reversely, a smooth (rather than a sharp) texture enhanced perception of (vanilla) ice cream sweetness. These findings indicate that expectations generated by surface textures influence subsequent taste evaluations.

Although occurrences of cross-modal correspondences are common throughout daily experience, accounting for them is less straightforward (Deroy, Crisinel, & Spence, 2013). Previous research underscores the relevance of the embodied cognition framework for explaining correspondences between design factors and food experience (Van Rompay & Fennis, 2019; Van Rompay & Ludden, 2015). However, understanding of associations between saltiness and specific surface textures is very limited. Inspired by research addressing correspondences between music and basic taste sensations (showing that musical representations corresponding to salty taste were characterized as *rough* and *irregular*; Mesz, Trevisan, & Sigman, 2011), Van Rompay and Groothedde (2019) recently demonstrated that customers at a supermarket rated potato chips as saltier when sampled from a rough (rather than a smooth) surface texture.

To understand couplings between saltiness and tactile aspects, Van Rompay and Groothedde (2019) hint at an associative learning explanation (cf. Deroy et al., 2013), centering on visual and tactile impressions arising in interactions with salt crystals (i.e., their *rough* and *irregular* character, and how they look and feel in one's hands). Hence, because of these recurring experiences with salt (crystals), we may associate saltiness with roughness and irregularity, and, vice versa, these characteristics may trigger saltiness associations when encountered in the 'right' context (i.e., when consuming salty foods from a bowl with these tactile properties).

1.2. Expectations and (dis)confirmations

Although most studies so far align with the notion of cross-modal correspondence by showing that expectations generated in one modality (i.e., touch) transfer to another (taste), in aforementioned study (Van Rompay & Groothedde, 2019), surface texture design did *not* influence saltiness evaluation of zero-salt chips. In other words, whereas an *assimilation* effect occurred when the consumption experience did not deviate too much from expectations triggered by the sample cup (as was the case with two regular chips variants used in this study), the effect disappeared when the gap between expectations and the consumption experience became too large, as was the case for participants who sampled zero-salt chips from the rough bowl.

This finding aligns with previous research showing that the gap between expectations (formed prior to tasting) and actual consumption experiences (i.e., the size of anticipation–reality divergence) is all-important (Davidenko et al., 2015; Verastegui, Van Trijp, & Piqueras-Fiszman, 2019; Shankar et al., 2010; Yeomans, Chambers, Blumenthal, & Blake, 2008). For instance, Yeomans et al. (2008) studied the interplay between expectations generated by food labels and subsequent taste evaluations. They showed that when participants were exposed to an ice-cream label generating strong expectations of a sweet flavor, but subsequently tasted a very salty (rather than sweet) ice cream instead, sweetness ratings decreased, clearly demonstrative of a contrast (rather than assimilation) effect. Likewise, Shankar et al. (2010) demonstrated that color cues can facilitate flavor identification, but only under conditions of low discrepancy between expectations triggered by drink color and flavor identity.

These combined findings show that when the gap between expectations and subsequent consumption experiences becomes too large, the source of the initial expectation (e.g., drink color, sample cup or package) is discounted (Shankar et al., 2010; Wang, Reinoso Carvalho, Persoone & Spence, 2017), and taste evaluations shift in the opposite direction (Hovland, Harvey, & Sherif, 1957; Schifferstein, 2001). However, as of yet, there is no research systematically varying tactile design features and (corresponding) levels of saltiness. That is, in Van Rompay and Groothedde (2019), a rough and irregular surface texture design was created by painting over a smooth sample bowl with plaster paint. Furthermore, existing potato chips brands were used which not only differed in salt contents, but also in terms of food structure and taste.

Using a 3D printing procedure in the current research, the present study aimed to disentangle roughness from irregularity (by distinguishing between a 1] smooth texture, 2] a rough texture, and 3] a rough *and* irregular texture) in order to further pinpoint which design aspect is primarily responsible for heightening saltiness impressions (explorative research question). Furthermore, rather than using existing branded products (Van Rompay & Groothedde, 2019), we selected bouillon soup in the current study in order to systematically vary salt contents, resulting in a low-salt, medium-salt, and high-salt bouillon variant.

Based on the foregoing, it is expected that saltiness impressions are enhanced (i.e., demonstrative of 'assimilation') for the medium-salt and high-salt variants sampled from the '*rough*' and '*rough and irregular*' cups. However, for the low-salt variant, it is expected that sampling from the '*rough*' and '*rough and irregular*' cups does *not* enhance saltiness impressions and may even backfire as the gap between saltiness expectations and actual salt contents becomes (too) large (resulting in a 'contrast' effect). Furthermore, we expect that a texture which enhances saltiness perceptions also boosts taste intensity (a measure closely related to saltiness perception; Van Rompay & Groothedde, 2019). Additionally, considering consumers' preferences for salty foods (and corresponding dislike for a 'bland' flavor; Stein et al., 2012), a texture that enhances saltiness perceptions should positively influence taste liking and willingness to try as well.

2. Method

2.1. 3D-printed cups

A series of sample cups with either a smooth, rough, or rough and irregular surface texture were 3D-printed. The cups were 3D-printed on an Ultimaker 2, with a durable, black PLA material in an FDM process (with 0.1-millimeter precision). The printed models were designed to fit as a sleeve around a heat-resistant, paper cup (to be replaced per subject for hygienic purposes). As for measurements, the cups are 60 mm high with a top radius of 60 mm, bottom radius of 30 mm, and wall thickness of 1 mm (see Fig. 1).

The rough cup has a surface texture procedurally generated with a noise pattern. The rough/irregular cup resembles carved out rock or wood. The texture is procedurally generated using a random pattern of points as input for a Voronoi diagram. The surface is protruded along the normal vector following a curve from seed towards the edge of each Voronoi cell.

2.2. Pretest 1

A pre-test was conducted to investigate whether the 3D-printed cups were perceived as realistic and whether the 'tactile feel' of the sample cups was correctly identified. To this end, 15 participants (7 male and 8 female) looked at, and touched, the three different cups (i.e., empty cups without paper cup and contents inside). Using a 7-point Likert scale (1 = totally disagree/ 7 = totally agree), the extent to which the cups were perceived as realistic was measured with the items '*This cup is suitable for drinking*', '*This cup feels nice*', '*It is realistic to drink from this cup*' and '*This cup fits the product type*' (Cronbach's alpha = 0.83). Item scores were summarized and averaged to arrive at an overall score for perceived realism. Results show that the cup with the smooth surface texture (M = 4.85, SD = 0.31), the cup with the rough surface texture (M = 4.75, SD = 0.37) and the cup with the rough/irregular surface texture (M = 4.78, SD = 0.34) all score relatively high on perceived realism (one-sample t tests reveal no significant differences between the means; all p's > 0.10).

As for tactile impression, participants rated (using 5-point bipolar scales) the extent to which the cups felt rough/smooth, granular/even, hard/soft, and stingy/smooth on their skin (Cronbach's alpha = 0.74). Again, scores were summarized and averaged to arrive at an overall score for tactile impression. Results indicate that the cup with the smooth surface texture (M = 4.90, SD = 0.12) was perceived as smoother than the cup with the rough surface texture (M = 3.89, SD = 0.34, $p < 0.01$), and the latter was in turn perceived as smoother than the cup with the rough/irregular surface texture (M = 2.27, SD = 0.24, $p < 0.01$). These combined results testify to the suitability of the 3D-printed cups (See Fig. 2 for finalized materials).

2.3. Pretest 2

A second pre-test was conducted to select three bouillon variants with respectively a low, medium and high salt level. To this end, we used a regular bouillon and a reduced-salt bouillon of the same brand (i.e., 'Maggi vegetable bouillon' and 'Maggi vegetable bouillon less salt' [Nestlé]; 0.6 g. per 100 ml and 0.1 g. per 100 ml respectively). Apart from these two variants, three other variants were created by adding salt to the two aforementioned bouillons, resulting in five different bouillon variants (0.1 g. per 100 ml, 0.3 g. per 100 ml, 0.5 g. per 100 ml, 0.6 g. per 100 ml, and 0.8 g. per 100 ml). Next, 15 participants (the same participants as in *Pretest 1*) tasted all five bouillons (which were presented in a random order). Salt perception was measured (using a 7-point Likert scale; 1 = totally disagree/ 7 = totally agree) with the statement '*This product tastes salty*'. To control for direct effects of saltiness levels on tastiness, participants also indicated to what extent they perceived the bouillon as tasty (i.e., '*This product is tasty*').

Table 1 presents the average saltiness and tastiness scores. As the maximum salt variant ('level 5′) differed markedly from the other variants in terms of tastiness, 'level 4′ was selected as the high-salt variant in addition to 'level 2 (medium-salt variant) and 'level 1′ (low-salt variant).

In sum, results from both pretests crystalize in a full-factorial 3 (surface texture: *smooth*, *rough*, *rough and irregular*) X 3 (product type:

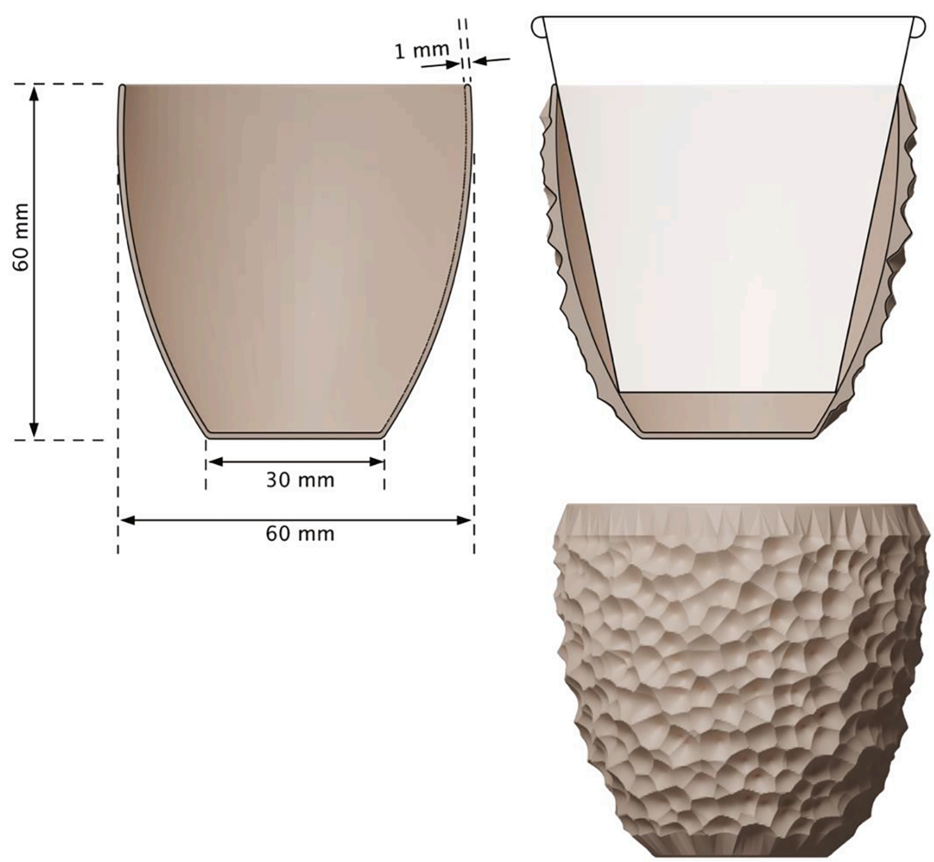

Fig. 1. Specifications of 3D-printed models.

Fig. 2. The 3D printed cups (from left to right: rough and irregular - smooth – rough – smooth with paper cup).

Table 1
Average saltiness and tastiness scores per salt level.

	Saltiness perception *M* (*SD*)	Tastiness *M* (*SD*)
Salt level 1	2.07 (0.70)[a]	5.07 (1.01)[a]
Salt level 2	4.07 (0.70)[b]	5.93 (1.16)[a]
Salt level 3	5.47 (0.52)[c]	6.27 (0.59)[a]
Salt level 4	6.00 (0.76)[d]	6.27 (0.70)[a]
Salt level 5	6.80 (0.41)[e]	4.40 (2.03)[b]

Note: Means with different superscript letters (a – e) differ from each other significantly ($p < .05$).

low-salt, medium-salt, high-salt) between-subjects design.

2.4. Participants

A total of 270 participants (49,6% female; mean age: 46.0 years; age range: 18–92 years) participated in the main study. They were approached at a local supermarket in a medium-sized Dutch city and asked to participate in a taste test. Participants were asked whether they were allergic to salt or whether they were on a low-salt diet. If this was the case, they were excluded from the study. Age ($F < 1$, ns) and gender (X^2 [1, N = 270] = 479.14, $p = .90$) were equally distributed across the conditions (see Table 2). Prior to data collection, this study was approved by the ethics committee of the University of Twente (request number: 190099).

2.5. Procedure

Upon agreement, participants received a brief introduction about the study (stating that the study revolved around first impressions of a new bouillon variant). Subsequently, they were handed a 2/3 cup (containing one of the three bouillon variants poured in the paper cup) and were asked to taste the product. After tasting, they filled out the (paper-based) questionnaire comprising the dependent measures. After completing the questionnaire, the participants were thanked for their participation.

Considering the research context (i.e., a supermarket rather than a lab setting) and the importance of keeping bouillon temperature constant (bouillon was prepared at home and transported in a vacuum flask), each afternoon taste session lasted between 90 and 120 min in which all participants tasted the same bouillon from the same cup. Each of the nine conditions (involving 30 participants) was run on a separate day.

Table 2
Participant demographics per condition.

Condition	N	Age	Gender %	
		Mdn	Male	Female
1	30	45.0	53.3	46.7
2	30	42.0	46.7	53.3
3	30	43.5	46.7	53.3
4	30	45.5	53.3	46.7
5	30	39.0	50.0	50.0
6	30	49.5	46.7	53.3
7	30	41.5	50.0	50.0
8	30	40.0	56.7	43.3
9	30	44.0	50.0	50.0

3. Measures

In order to assess perceived saltiness, participants were requested to indicate to what extent their agreed with the statement 'This product tastes salty', using a 7-point Likert scale (1 = totally disagree/ 7 = totally agree). Likewise, for taste intensity participants were requested to indicate to what extent their agreed with the statement 'This bouillon tastes intense'.

Taste liking was measured with the statements 'This product is delicious', 'I like the taste of this product', 'The taste of this product is just right' and 'The taste of this product appeals to me to' (Cronbach's alpha = 0.98). Again, participants were asked to indicate to what extent they agreed with the statements using a 7-point Likert scale (1 = totally disagree/ 7 = totally agree).

Finally, willingness to try was measured (using a 7-point Likert scale; 1 = totally disagree/ 7 = totally agree) with the statements 'When at the supermarket, I would consider buying this bouillon', 'When available at the supermarket, I would like to try this bouillon' and 'After tasting, I am interested in this bouillon' (Cronbach's alpha = 0.98). We used a 'willingness to try' (rather than a more conventional 'purchase intention' construct) as raising awareness and interest may be considered a first step (preceding the formation of purchase intentions) in promoting health behaviour change (Prochaska & Velicer, 1997).

3.1. Data analysis

For all constructs, items were summarized and averaged to arrive at a total score for each outcome measure. Univariate analyses of variance (ANOVA) were used to analyze main and interaction effects of surface texture and salt level on the outcome measures. In case of significant interaction effects, pairwise comparisons were used to determine which group differences were statistically significant.

4. Results

We discuss the effects of salt perception and cup texture, as well as their interaction effects on the dependent variables. For a concise overview of the main and interaction effects, see Table 3. For a detailed overview of the interaction effects (including within condition effects) see Figs. 3–5.

Table 3
Overview of main and interaction effects.

	salt level	cup texture	interaction
Salt perception	$F(2, 261) = 881.57$ $p < .001$, $\eta^2 = 0.87$	$F(2, 261) = 37.31$ $p < .001$, $\eta^2 = 0.22$	$F(4, 261) = 12.77$ $p < .01$, $\eta^2 = 0.32$
Taste intensity	$F(2, 261) = 1241.46$ $p < .000$, $\eta^2 = 0.91$	$F(2, 261) = 1.39$ $p = .251$	$F(4, 261) = 0.90$ $p = .462$
Taste liking	$F(2, 261) = 401.81$ $p < .001$, $\eta^2 = 0.76$	$F(2, 261) = 1.81$ $p = .165$	$F(4, 261) = 5.30$ $p < .001$, $\eta^2 = 0.08$
Willingness to try	$F(2, 261) = 328.64$ $p < .001$, $\eta^2 = 0.72$	$F(2, 261) = 4.83$ $p = .009$, $\eta^2 = 0.04$	$F(4, 261) = 5.97$ $p < .001$, $\eta^2 = 0.084$

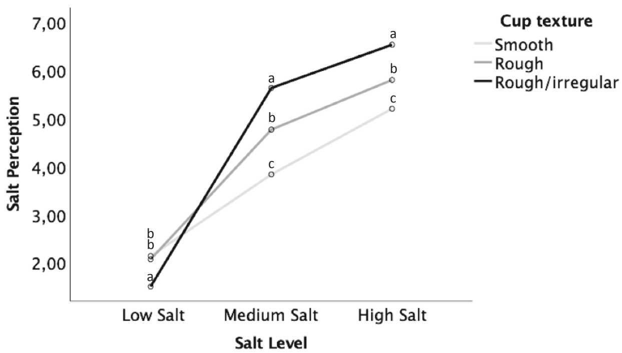

Fig. 3. Salt perception as a function of cup texture. Note: Within each condition of salt level, different superscript letters indicate significant differences between cup texture conditions.

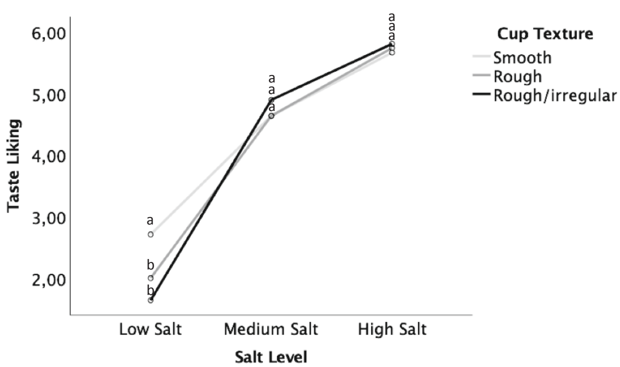

Fig. 4. Taste liking as a function of cup texture. *Note*: Within each condition of salt level, different superscript letters indicate significant differences between conditions of cup texture.

4.1. Salt perception

An ANOVA with salt level and cup texture as between-subject factors and salt perception as dependent variable showed a main effect of salt level (F (2, 261) = 881.57, $p < .001$, $\eta^2 = 0.87$). Specifically, the high-salt bouillon ($M = 5.84$, $SD = 0.83$) was perceived as saltier than the low-salt bouillon ($M = 1.90$, $SD = 0.69$, $p < .001$) and the medium-salt bouillon ($M = 4.74$, $SD = 1.00$, $p < .001$). In addition, the medium-salt bouillon ($M = 4.74$, $SD = 1.00$) was perceived as significantly saltier than the low-salt bouillon ($M = 1.90$, $SD = 0.69$, $p < .001$).

More importantly, cup texture significantly influenced perceived saltiness (F (2, 261) = 37.31, $p < .001$, $\eta^2 = 0.22$). When the product was

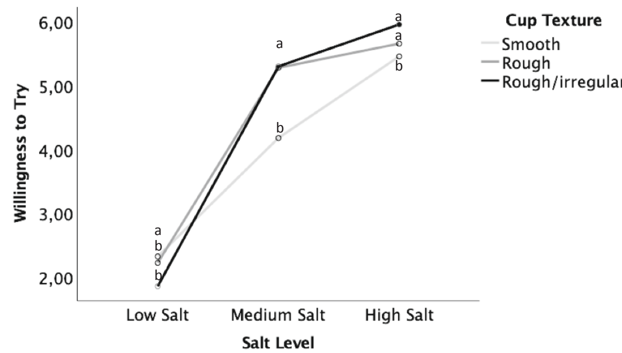

Fig. 5. Willingness to try as a function of cup texture. Note: Within each condition of salt level, different superscript letters indicate significant differences between cup texture conditions.

sampled from the cup with the rough/irregular cup ($M = 4.56$, $SD = 2.27$), perceived saltiness was higher compared to the cup with the smooth texture ($M = 3.72$, $SD = 1.45$, $p < .001$) and the rough texture ($M = 4.21$, $SD = 1.72$, $p = .001$). In addition, the cup with the rough texture ($M = 4.21$, $SD = 1.72$) resulted in a higher salt perception than the smooth texture ($M = 3.72$, $SD = 1.45$, $p < .001$).

In line with our predictions, there was a significant interaction effect between cup texture and saltiness level on perceived saltiness (F (4, 261) = 12.77, $p < .01$, $\eta^2 = 0.32$; see Fig. 3). When medium-salt bouillon was sampled, the cup with the rough/irregular texture ($M = 5.63$, $SD = 0.49$) resulted in a significantly higher salt perception than the cup with the smooth texture ($M = 3.83$, $SD = 0.79$, $p < .001$) and the rough texture ($M = 4.77$, $SD = 0.73$, $p = .001$). Furthermore, the cup with the rough texture ($M = 4.77$, $SD = 0.73$) resulted in a significantly higher salt perception than the cup with the smooth texture ($M = 3.83$, $SD = 0.79$, $p < .001$).

When high-salt bouillon was sampled, cup texture influenced perceived saltiness in a similar way. Sampling from the cup with the rough/irregular texture resulted in a higher salt perception ($M = 6.53$, $SD = 0.51$) compared to the cup with the smooth texture ($M = 5.20$, $SD = 0.71$, $p < .001$) and the rough texture ($M = 5.80$, $SD = 0.66$, $p < 0.001$). Moreover, sampling from the cup with the rough texture resulted in a higher salt perception compared to the cup with a smooth texture ($M = 5.20$, $SD = 0.71$, $p < .001$). These findings are clearly indicative of assimilation effects in which saltiness perceptions follow expectations triggered by surface texture.

However, for the low-salt variant, the direction of the effect reverses, demonstrating contrast rather than assimilation. Specifically, the cup with the smooth texture ($M = 2.13$, $SD = 0.68$) triggered a higher salt perception than the rough/irregular texture ($M = 1.50$, $SD = 0.57$, $p < .001$). However, there was no difference between the cup with the smooth texture ($M = 2.13$, $SD = 0.68$) and the cup with the rough texture ($M = 2.07$, $SD = 0.64$; $p = .692$).

4.2. Taste intensity

An ANOVA with salt level and cup texture as between-subject factors and *taste intensity* as dependent variable revealed a main effect of salt level (F (2, 261) = 1241.46, $p < .000$, $\eta^2 = 0.91$). The high-salt bouillon ($M = 6.22$, $SD = 0.73$) resulted in a significantly higher taste intensity than the medium-salt bouillon ($M = 5.09$, $SD = 0.77$, $p < .001$), which in turn had a higher taste intensity than the low-salt bouillon ($M = 1.41$, $SD = 0.49$, $p < .001$). Surprisingly, however, the main effect of cup texture on taste intensity was not significant (F (2, 261) = 1.39, $p = .251$). Likewise, the interaction effect between cup texture and salt level was non-significant (F (4, 261) = 0.90, $p = .462$).

4.3. Taste liking

An ANOVA with salt level and cup texture as between-subject factors and *taste liking* as dependent variable yielded a significant main effect of salt level (F (2, 261) = 401.81, p < .001, η^2 = 0.76). The high-salt bouillon (M = 5.73, SD = 0.89) resulted in a higher taste liking than the medium-salt bouillon (M = 4.71, SD = 0.70, p < .001), which in turn resulted in a higher taste liking than the low-salt bouillon (M = 2.12, SD = 1.11, p < 0.001). The main effect of surface texture on taste liking was not significant (F (2, 261) = 1.81, p = .165).

However, the interaction effect between cup texture and salt level on taste liking *was* significant (F (4, 261) = 5.30, p < .001, η^2 = 0.08). Specifically, for low-salt bouillon, taste liking was higher when sampled from the smooth-textured cup (M = 2.71, SD = 1.43) compared to the rough-textured cup (M = 2.00, SD = 0.83, p = 0.02) and the rough/irregular textured cup (M = 1.64, SD = 0.64, p < .001). The difference between the rough and the rough/irregular-textured cups was not significant (p = .117). Within the medium and high-salt conditions, the differences between the surface textures were non-significant (p's > 0.25; see Fig. 4).

4.4. Willingness to try

An ANOVA with salt level and cup texture as between-subject factors and *willingness to try* as dependent variable yielded a significant main effect of salt level (F (2, 261) = 328.64, p < .001, η^2 = 0.72). The high-salt variant resulted in a significantly higher willingness to try (M = 5.69, SD = 0.97) than the medium-salt product (M = 4.92, SD = 0.98, p < .001) and the low-salt variant (M = 2.13, SD = 1.12, p < .001). Furthermore, the medium-salt variant (M = 4.92, SD = 0.98) resulted in a higher willingness to try than the low-salt variant (M = 2.13, SD = 1.12, p < .001).

The main effect of cup texture was also significant (F (2, 261) = 4.83, p = .009, η^2 = 0.04). The smooth texture (M = 3.99, SD = 1.79) results in a lower willingness to try than the rough texture (M = 4.39, SD = 1.80, p = .007) and the rough/irregular texture (M = 4.37, SD = 1.93, p = .009). There was no significant difference between the rough and the rough/irregular condition, p = .919.

Furthermore, the interaction between the cup texture and salt level was significant (F (4, 261) = 5.97, p < .001, η^2 = 0.084; see Fig. 5). In the medium-salt condition, the smooth texture (M = 4.18, SD = 1.07) resulted in a lower willingness to try than the rough texture (M = 5.28, SD = 0.76, p < .001) and the rough/irregular texture (M = 5.30, SD = 0.63, p < .001). There was no significant difference between the rough and the rough/irregular structure, p = .148.

In the high-salt condition, there was no difference in willingness to try between the smooth texture and the rough texture, p = .429, and between the rough texture and the rough/irregular texture, p = .236. However, the smooth texture (M = 5.46, SD = 1.09) resulted in a lower willingness to try than the rough/irregular texture (M = 5.96, SD = 0.58, p = .049).

In the low-salt condition, there was no difference in willingness to try between the smooth texture and the rough texture, p = .693, and the rough texture and the rough/irregular texture, p = .148. However, the smooth texture (M = 2.32, SD = 1.54) resulted in a marginally higher willingness to try than the rough/irregular texture (M = 1.86, SD = 0.79, p = .066).

5. Discussion

The results of this study underscore the potential of surface textures for influencing saltiness perceptions, and for stimulating taste liking and healthy behaviors (i.e., willingness to try healthy product variants). Importantly, this means that negative evaluations frequently voiced in relation to reduced-salt foods can be counteracted through surface texture design.

Importantly, our results are in line with previous research demonstrating effects of material type and texture on food evaluation (Carvalho et al., 2020; Van Rompay & Groothedde, 2019). However, our findings clearly show that such effects do not necessarily entail assimilation effects in which impressions from one modality (e.g., touch) are transferred to another (e.g., taste). Specifically, our findings extend previous research by showing that when the gap between expectations (formed prior to tasting) and subsequent consumption experiences becomes too large, contrast rather than assimilation effects occur (Davidenko et al., 2015; Verastegui-Tena et al., 2019; Yeomans, Chambers, Blumenthal, & Blake, 2008). To our knowledge, this is the first study demonstrating that such effects may follow from theory-driven applications of 3D-printed surface textures.

However, the effects varied considerably over the different outcome variables. For instance, whereas for salt perception and willingness to try, differences between the textures were obtained within the medium and high salt conditions, for taste liking, differences between the textures were only significant within the low-salt condition. As for taste intensity, surprisingly no effects were found for surface texture. Thus, whereas a very strong effect of salt level on taste intensity was observed (mirroring the commonly heard complaint that salt-reduced foods have a bland taste), the effect of cup texture was non-significant.

Likewise, pretest results and our findings on salt perception testify to the additional value of combining rough and irregular features for boosting salt perception, but again, these differences did not surface in the results for taste liking and willingness to try. Clearly, these combined findings call for follow-up research disentangling the relationships between cup texture, perceived saltiness and taste intensity.

In terms of practical implications, our findings have clear relevance as reducing food saltiness is important across many product types and settings ranging from hospitals and nursing homes (e.g., salt-reduced meals for patients; Van Wymelbeke et al., 2020), entertainment settings (e.g., consumption of salty snacks during movie showings in cinemas), to supermarkets and bars and restaurants. Apart from sample cups, surface textures could also be applied on tableware (ranging from cutlery and chopsticks to table mats and serving trays), (ready-to-consume) product packaging, and even on food itself (Slocombe, Carmichael, & Simner, 2016). Moreover, a recent study addressing the influence of a visual cue on perceived flavor intensity of rice (i.e., dehydrated baby spinach leaves evenly dispersed throughout the rice) testified to the effectives of counteracting a bland taste by means of visual cues boosting flavour intensity perceptions (Hartley et al., 2021). Clearly, these combined findings point at the potential of a multisensory approach (combining tactile and visual cues) to promote healthy food consumption.

Considering the developments and opportunities provided by 3D-printing, such multi-sensory endeavors should become even more feasible and cost-efficient in the upcoming years. Again, our findings show that careful consideration of the gap between expectations and actual food experience is required. However, considering the assimilation effects obtained throughout our study (mirroring the assimilation effects reported on in Hartley et al., 2021), our findings clearly stress the potential of (tactile and multisensory) design for promoting reduced-salt (but arguably not for zero-salt) food options.

As for limitations, it should be pointed out that this study focused on a single product only. However, our findings align with previous research centering on saltiness in relation to salty snacks (i.e., potato chips, Van Rompay & Groothedde, 2019), likewise demonstrating the potential of a rough, rather than smooth, surface texture for enhancing saltiness impressions. Although our findings show that more complex textures combining multiple tactile aspects (roughness and irregularity in this study) can have additional value, our findings do not warrant firm conclusions as differences varied across outcome variables.

Furthermore, out findings are silent on longer-term effects of design factors (and surface textures in particular) on food experience. Thus, although potential applications of surface textures are many, research has not addressed the question of how they influence food experience over time. For instance, when implementing surface textures on product packaging, do effects transpire after multiple purchases, also taking into account habituation to 'novel' sensations triggered by surface textures?

And to what extent does consumer awareness play a role? For instance, self-report measures were used in this study. As a result, it is possible that experimenter demand effects played a role, resulting in effects that support our hypotheses. On the other hand, surface textures might have even stronger effects in situations where consumer responses are measured on a more implicit level. For instance, Van Ooijen, Fransen, Verlegh, and Smit (2017) found that packaging design cues have a stronger influence on healthiness associations when those associations are measured on an implicit, rather than explicit, level, arguably because implicit processes do not require an intention to evaluate the product (Gawronski & Bodenhausen, 2006; Strack, Werth, & Deutsch, 2004). Translated to the current context, a product choice task could be used (in a simulated shopping episode) to investigate whether effects of tactile cues not only transpire in self-report measures, but also increase choice likelihood of reduced-salt variants.

Follow-up research could also incorporate a saltiness expectation measure to verify our claim that the gap between expectations formed prior to testing and the actual consumption experience determines the direction of effects (i.e., whether applications of surface textures trigger *contrast* or *assimilation* effects). In the present research, saltiness expectations were not included to minimize time demands on participants (i.e., shoppers at a supermarket with limited time). Additionally, follow-up studies could increase sample size which was admittedly relatively small considering the between-subjects design employed. Although using a within-subjects design would require less participants, it has the disadvantage of facilitating hypothesis guessing (i.e., triggering demand effects) and, by consequence, yielding inflated results (see Biggs et al., 2016; Hartley et al., 2021 for further discussion on this issue).

Also, the surface texture manipulations not only influenced tactile impressions but the visual appearance of the stimuli as well. Although it is feasible to block visual access to the surface textures (e.g., by blindfolding participants), such an approach would not do justice to everyday encounters between consumers and products in which visual and tactile cues are usually conflated. Finally, although we used two bouillon variants of the same brand (i.e., a regular and a reduced-salt variant), we cannot fully rule out that minor differences in food composition may have influenced our findings.

Awaiting follow-up studies addressing these and other research questions, the results of the present study testify to the potential of design for promoting healthy food choices while at the same underscoring the importance of carefully studying the interplay between (extrinsic) design factors and (intrinsic) food contents.

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